Multi physics model of the processes inside EUV source chamber

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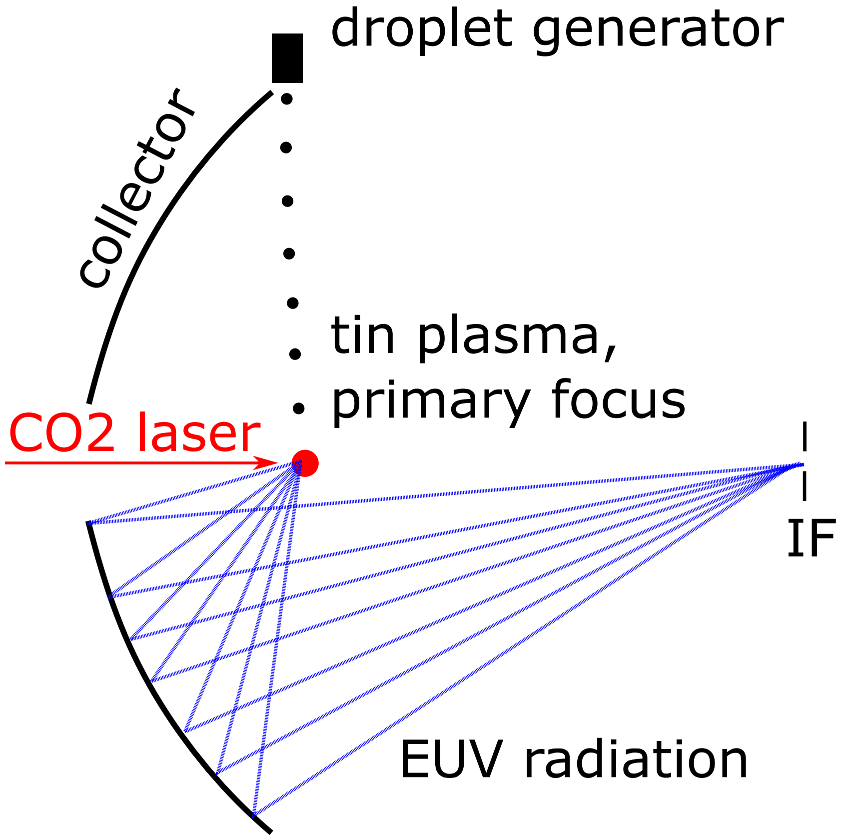
Outline

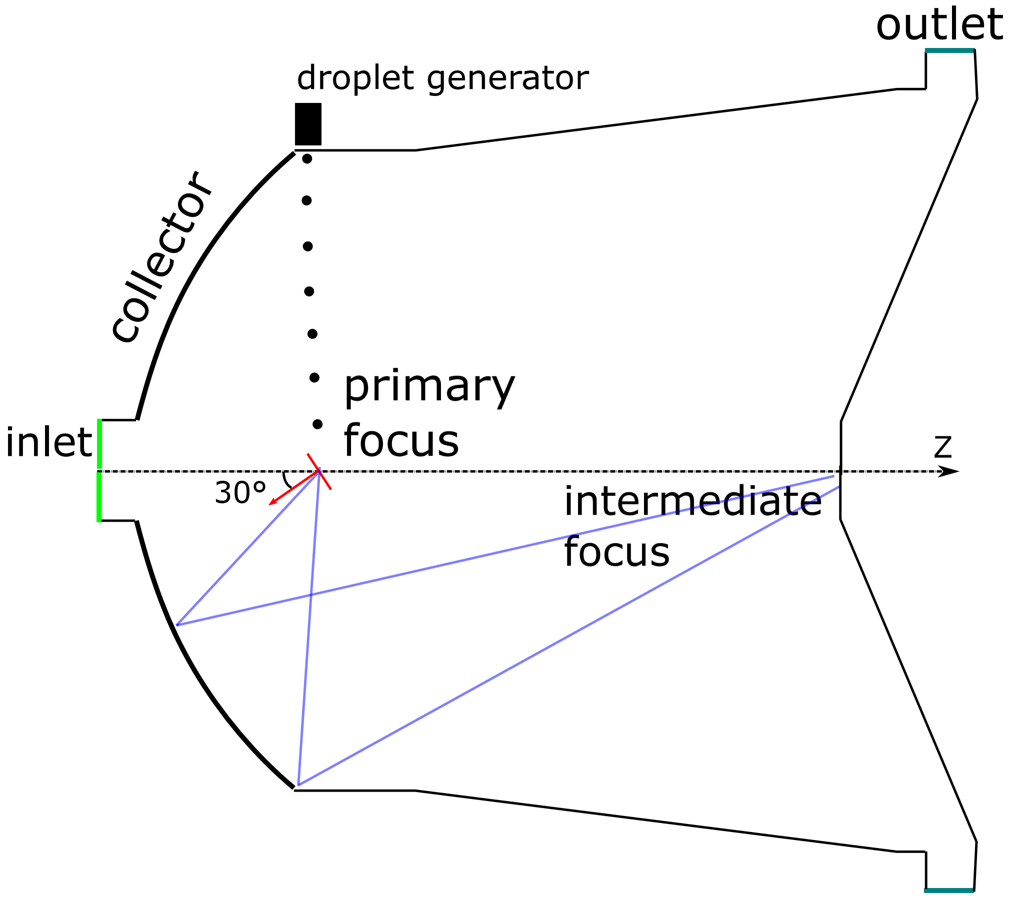
- Part I: Model overview
  - Example of model output
  - Included physics
  - Model structure
- Part II: Pressure vs flow optimal conditions

Motivation for flow model



- Collector mirror need to be protected from tin debris
- Two main approaches:
  - Gas flow
  - Gas flow + B-field
- Goal: fast transient 3D model for flow + plasma conditions

Test configuration of LPP EUV source chamber



Target:

- Disk-like Sn target, mass equal to 30 μm droplet
- 30° disk tilt

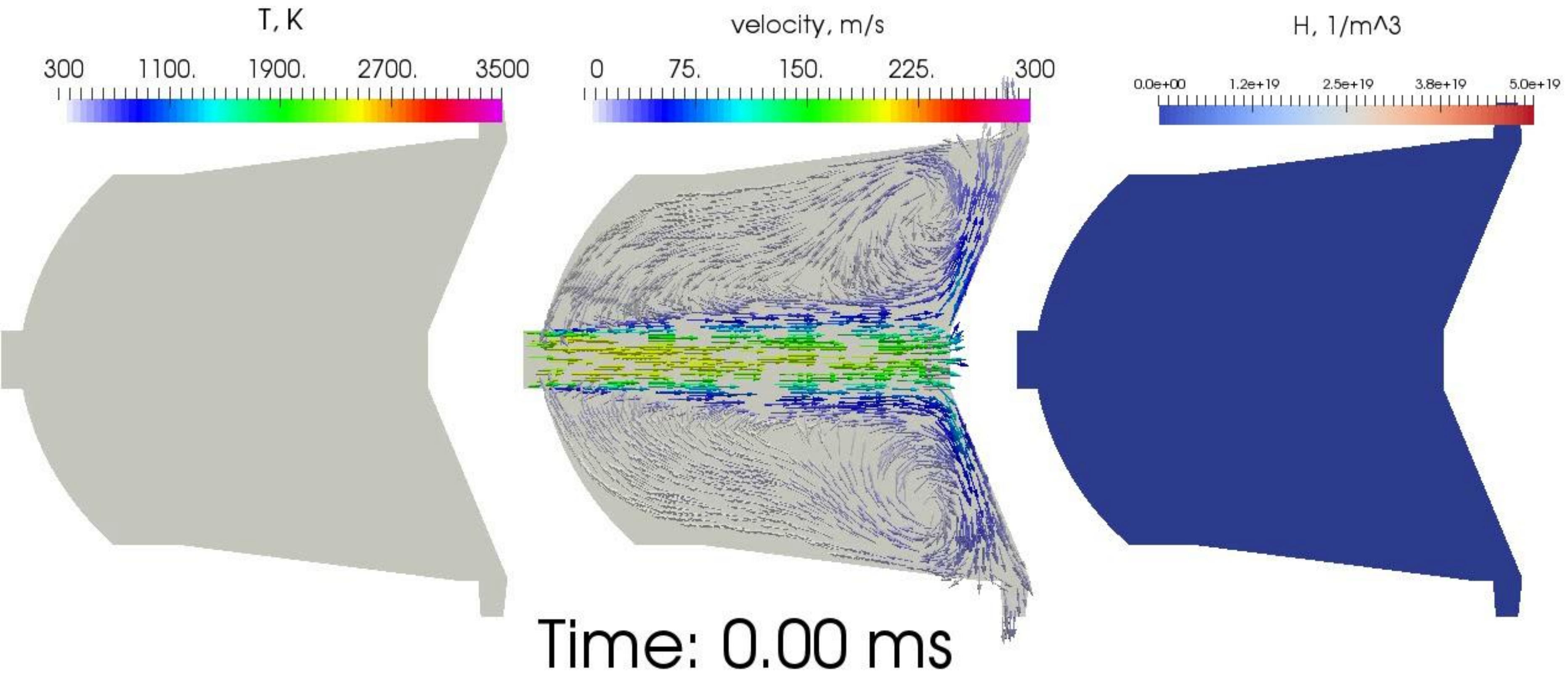
Laser:

- CO_2 main pulse
- ~100 mJ pulse energy
- 50 kHz operation frequency

Gas protection:

- H_2 central flow

Transient simulation for test configuration



Included physics

- Gas heating due to ions stopping
- Spectrally resolved WUV radiation absorption in gas
  - Reflection from collector, EUV to IF
- H2 dissociation

- Multi component diffusion
- Particulate debris tracking
- Set of surface & volume chemical reactions
  - Tin deposition to surfaces
  - Tin cleaning by atomic hydrogen

- Disturbance of the tin droplets trajectory by flow field

Relevant time & space scales hierarchy

(1) Laser pulse & hot tin plasma

- $t < 500$ ns, $h < 1$mm

(2) Ions stopping & radiation absorption

- $t \sim 1$ µs, h ~ chamber size

(3) pulse-to-pulse repetition time

- $t \sim 10$ µs

(4) Transport processes in chamber

- $t > 10$ ms, h ~ chamber size

Relevant time & space scales hierarchy

(1) Laser pulse & hot tin plasma

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- t ~ 1 μs,   h ~ chamber size

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- t ~ 10 μs

(4) Transport processes in chamber

- t > 10 ms, h ~ chamber size

Not resolved, input data

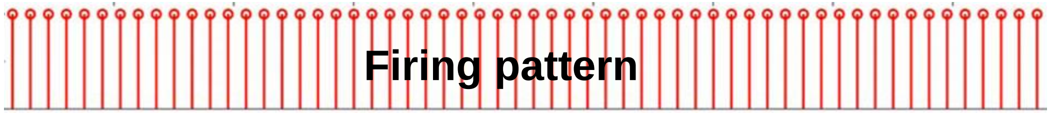
Partially resolved, time scale integrated out

Transient CFD

Model approach: CFD + plasma source

EUV plasma characteristics
- Ions: angular - energy distribution + charge states
- Radiation: angular resolved spectrum

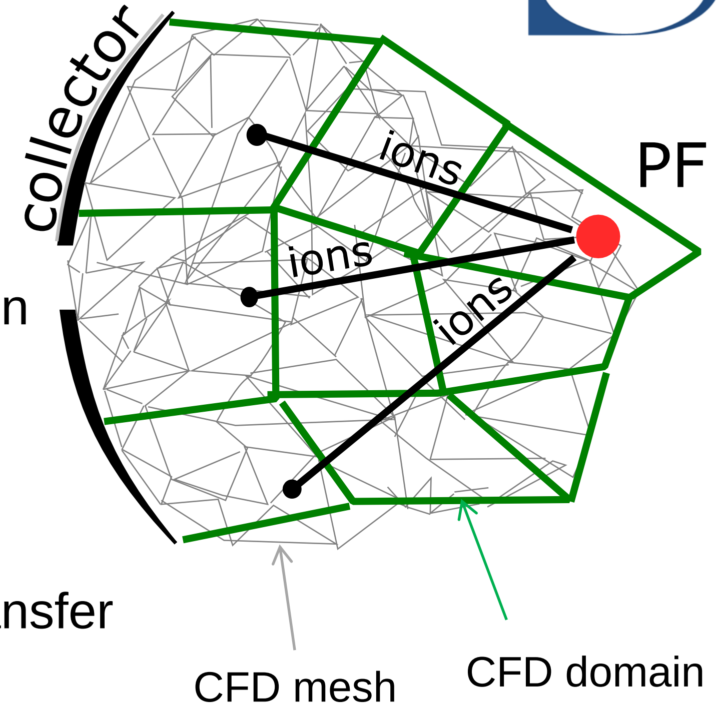
Plasma energy-mass-momentum source for CFD
- Particle tracing for ions
- Ray tracing for radiation



Computational fluid dynamics for multi-component gas
•Mesh accounts for complex vessel geometry

Performance is main challenge for simulations

- Goal: 100ms of simulation in ~50 hours
  - 1/3 time for source, 2/3 for CDF
- 100ms of source operation is ~ 5000 pulses
  - Have only ~ 10s real time per pulse !
- CFD uses domain decomposition for parallelization
  - CFD decomposition is not good for ray tracing
  - Huge number of transitions between domains
  - Off-the-shelf codes for CFD are likely to fail
- External ray/particle tracing solution need data transfer to/from CFD

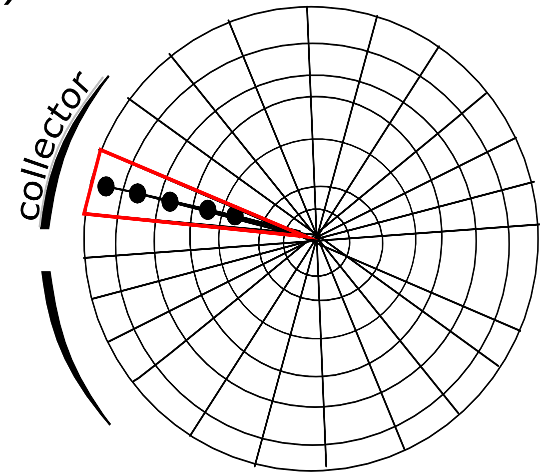


Task motivated simplification: structured grid

- Very large mass ratio between Sn and H2 -> small straggling
- Direct Sn – Sn collisions are rare

(collisions in tin plasma are covered by the input data)

- Ions and EUV input :
    - Likely to be smooth functions of polar angles
    - Known with finite accuracy (e.g. ~ 5deg for RZLINE)
    - Emitted from the same point for all pulses
      (on the scale of the chamber)

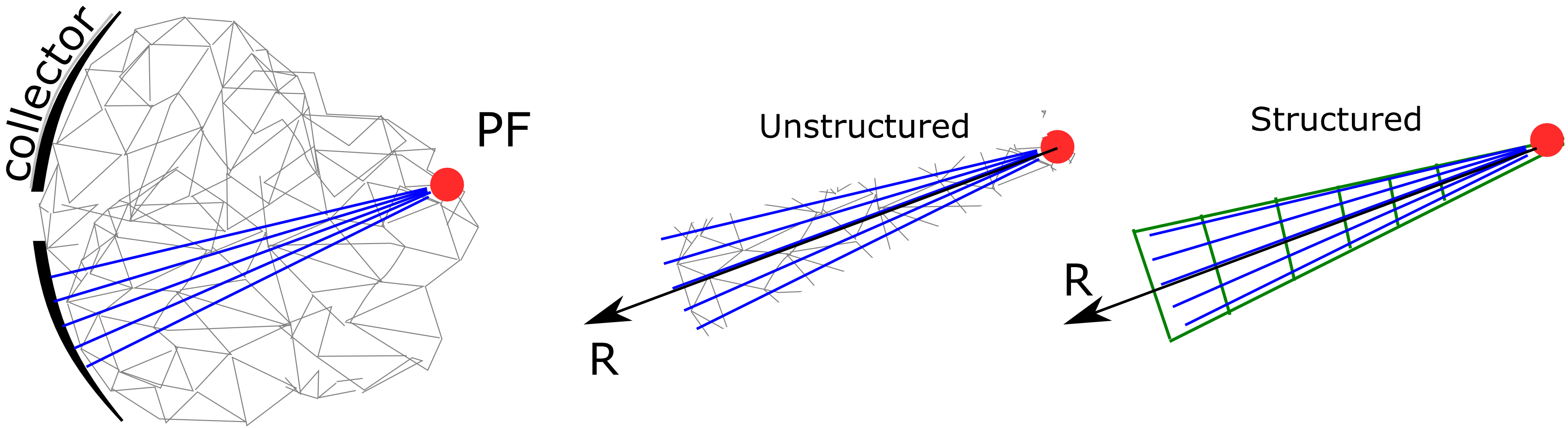


Ideal mesh: structured spherically symmetric mesh

- Path over grid is simple, lot of time for physics
- Interpolation is a data transfer to/from CFD

Interpolation operator is built using ray tracing

- Ion stopping and WUV absorption determined by density integrals
- Density integrals (i.e. ∫ρ(r)dr) should be the same on both grids
- Ray tracing' on botch grids yields interpolation coefficients



- The interpolation is computed only once per simulation
- Interpolation is reused for all pulses → major performance gain
- Density integral is conserved → accurate description of ion stopping

Sum up

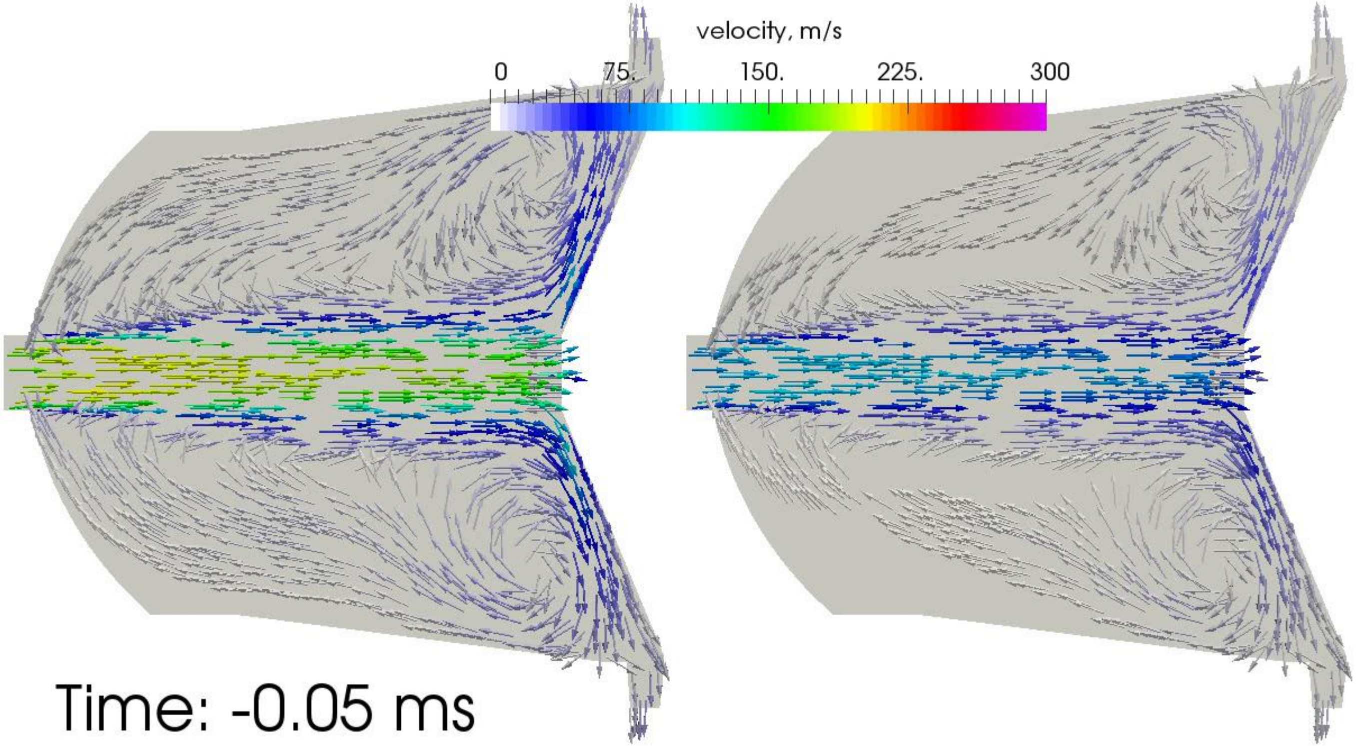
- The system have small parameters, e.g.
  - Mass ratio of H2 to Sn, and hence straggling for Sn stopping in H2
  - Ions and EUV are emitted by point source

- Structure grid for ions/euv allowed to accelerate simulations
and reach pulse-to-pulse time resolution

- Part of the performance gain is used to improve physics,
e.g. spectral resolved EUV absorption.

Part II: scan over parameters, pressure vs flow

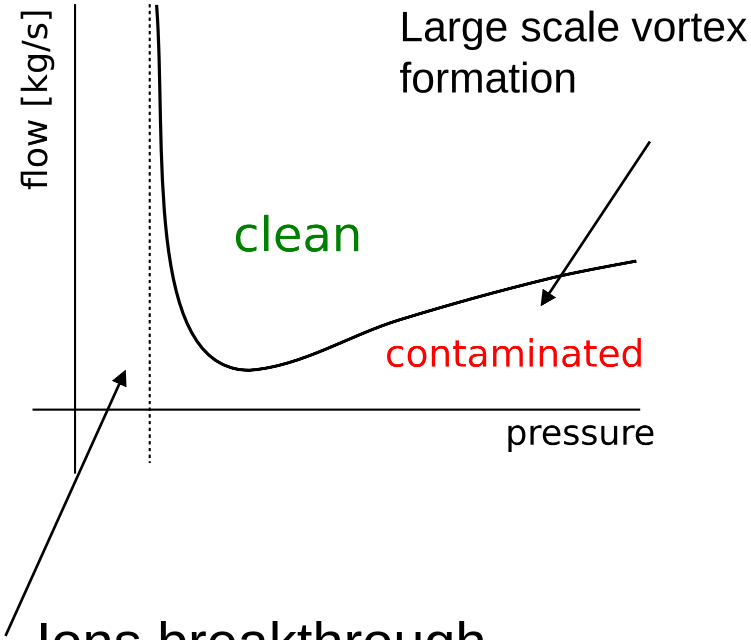
Interaction of plasma with center flow: pressure increase for constant flow



Higher pressure

- Imbalance between plasma induced force on flow and flow dynamic pressure lead to distortion of flow field and transport of tin to collector

Fast and slow contamination mode



Ions breakthrough

- Vortex formation lead to fast contamination of the collector (~ 0.1um/hour)
- There is a point with optimal flow conditions with minimal pressure and flow requirements
- The conditions are sensitive to shape of ions distribution, flow scheme, chamber geometry, etc.

Conclusions

- We have developed 3D transient model that couples energy and momentum input from tin plasma to the flow in the EUV source chamber
- The model can be used to optimize the chamber geometry, flow structure etc. for regime during source operation

Back up

Gas temperature near plasma focus point

- In 1cm near PF tin concentration is less than 1% of H_2
- The max gas temperature near PF is limited by H_2 dissociation
  - Dissociation constant ~ exp(T/T0)
  - Gas temperature is limited at ~ 5000K
- Thermal radiation is negligible, due to low gas density
- On length scales larger than 1cm the ionization degree is estimated as < 1e-4. Hence, the CFD approach can be used.

Transient EUV output